AD-782 519

REVIEW OF CANDIDATE STRUCTURAL MATERIALS FOR AN ARCTIC SURFACE EFFECT VEHICLE

A. G. S. Morton, et al

Naval Ship Research and Development Center

Prepared for:

Advanced Research Projects Agency

May 1972

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Report 3573

Review of Candidate Structural Materials for an Arctic Surface Effect Vehicle

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Md. 20034

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By

A. G. S. Morton and M. Silvergleit

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
ARPA Order No. 1676
Program Code No. ON10

[redacted]

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MATERIALS DEPARTMENT
Annapolis
Phase
RESEARCH AND DEVELOPMENT REPORT

May 1972

Report 3573

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Naval Ship Research and Development Center
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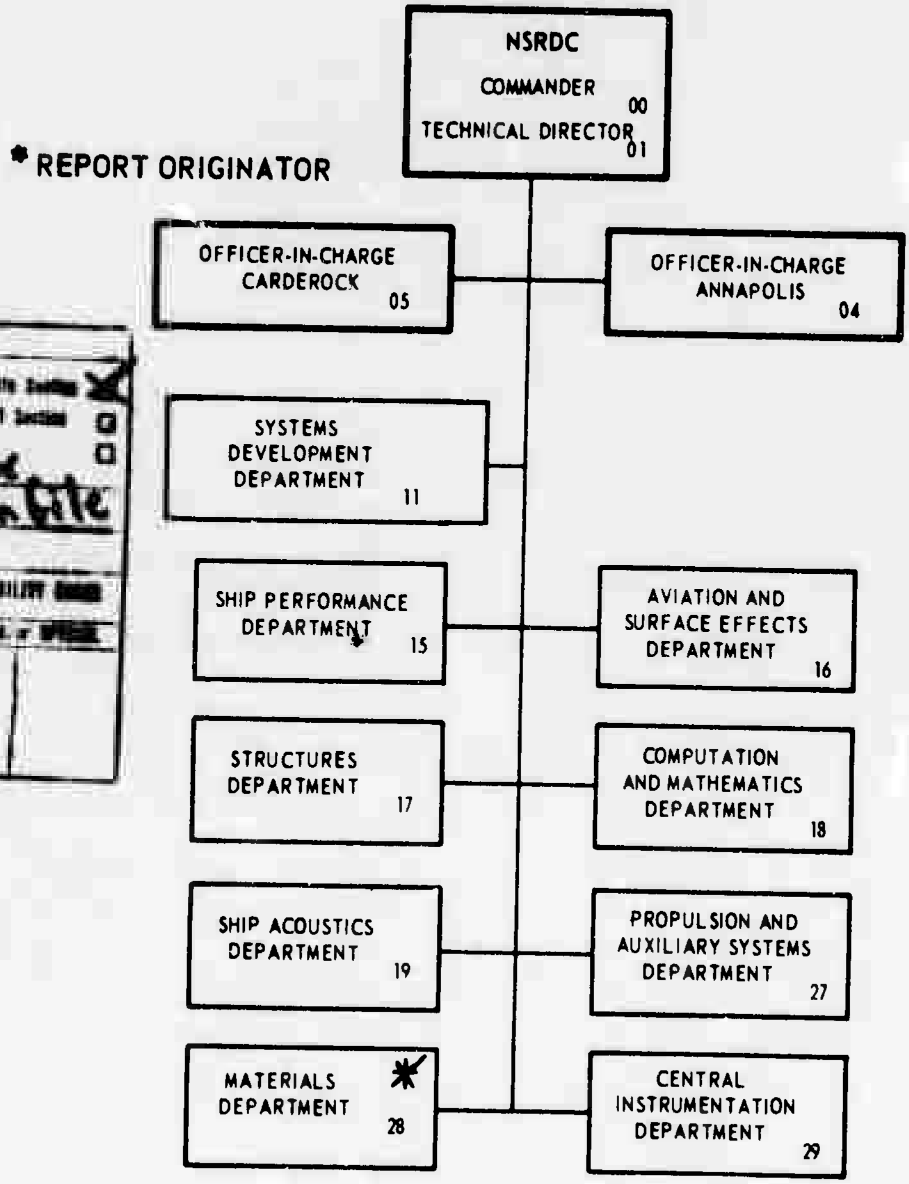

Security Classification UNCLASSIFIED

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Ship Research and Development Center Annapolis, Maryland 21402	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Review of Candidate Structural Materials for an Arctic Surface Effect Vehicle

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Phase Report

5. AUTHOR(S) (First name, middle initial, last name)

A. G. S. Morton and M. Silvergleit

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1972	39	40

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) 3573
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) 28-143
d.	

10

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	NSRDC

13. ABSTRACT

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Although most of the material properties are known, the specific application of an alloy to a particular section of the proposed craft is not possible, owing to the present lack of design details. From the structural materials point of view the most critical craft operating environment appears to be the summer open-ocean condition. There are, however, several unresolved problems imposed by the arctic environment and a discussion of these is included. The appendix is an annotated bibliography of selected surface effect vehicle references.

(Authors)

DD FORM 1 NOV 65 1473 (PAGE 1)

0102 014 6600

UNCLASSIFIED

Security Classification

14

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Arctic environment						
Surface effect vehicle						
Structures						
Materials						
Operating requirements						
Alloys						
Material characteristics						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

DEPARTMENT OF THE NAVY

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

BETHESDA, MD. 20034

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This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Arctic SEV Program Office, Systems Development Department.

May 1972 28-143 // Report 3573

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ADMINISTRATIVE INFORMATION

This study was conducted for the Arctic Surface Effect Vehicle Program Office of this laboratory through support provided by the Advanced Research Projects Agency of the Department of Defense.

This work was performed in the Alloy Development Branch of the Metals Division, Materials Department. This report was prepared under Work Unit 1-1130-280 and constitutes the structural materials section of milestone 7 for fiscal year 1971, in the 1 May 1971 Research and Technology Work Unit Summary.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
ADMINISTRATIVE INFORMATION	iv
INTRODUCTION	1
MATERIALS AT LOW TEMPERATURES	2
MATERIAL CHARACTERISTICS	4
Aluminum Alloys	4
Titanium Alloys	9
Nickel Alloys	12
Steels	13
Structural Plastics	15
COST CONSIDERATIONS	21
Aluminum	21
Steel	21
Nickel	22
Titanium	22
Structural Plastics	22
UNRESOLVED MATERIALS PROBLEMS IMPOSED BY THE ARCTIC ENVIRONMENT	23
Metals	23
Structural Plastics	24
SUMMARY	25
TECHNICAL REFERENCES	26
APPENDIXES	
Appendix A – Annotated Bibliography of Selected SEV References (4 pages)	
INITIAL DISTRIBUTION	

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INTRODUCTION

The unique nature of the arctic surface effect vehicle (ASEV) imposes complex structural and materials requirements upon the designer. At this time only the general operating requirements of range, speed, payload size, etc, are known, but these factors are sufficient to indicate the nature of the contemplated craft. The operating environment is fairly well characterized and when coupled with the vehicle characteristics provide the materials engineer sufficient criteria for an initial evaluation of potential structural materials.

This initial survey of candidate materials for the ASEV is limited to those considered to be within the present state of the art for high performance vehicles. Some background information on materials for high performance vessels is available due to work performed by the Surface Effects Ship Program Office, Amphibious Assault Landing Craft, and Hydrofoil Programs. Among these programs are many areas of common interest with respect to materials properties, especially fatigue properties. The one distinguishing requirement for most of the materials to be used in the ASEV is the ability to maintain integrity at low temperatures (−65° F).* The materials programs for these high performance vessels are being closely coordinated so that the cost of obtaining the required data of common interest can be shared.

There are two areas in which background information on materials for high performance vessels has been developed. The first area concerns materials properties. Several material property surveys have been prepared that identify candidate alloys for high performance craft.[1,2] The materials included in these surveys ranged from the conventional naval structural materials (e.g., HY−80 steel) to the high strength-to-weight ratio titanium and nickel-base alloys. Each of the advanced materials have their particular problems, but of course, offer attractive structural weight fractions on high performance craft. For the ASEV, it will probably be necessary to choose structural materials that achieve an efficient, economical balance between conventional metals of low strength-to-weight ratio, that are inexpensive, easily fabricated and repaired, and the metals of high strength-to-weight ratio that are relatively expensive and difficult to fabricate.

The other area in which background information has been generated is in the analysis of fabrication methods.[3,4] This analysis is very important in assessing the worth of a particular structural alloy in that it delineates the cost and weight penalties with respect to various construction methods. An analysis of this kind will be essential at a later stage in the ASEV program.

It is essential to realize that the ASEV is a marine structure and that one of the most important material requirements is excellent sea-water corrosion resistance. Although the vehicle may be exposed to salt water only for 3 months a year, and fresh water for perhaps an additional 4 to 6 weeks, serious and costly damage could occur to critical vehicle parts if corrosion-susceptible alloys were chosen. This will be especially true for underside surfaces

*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.
[1]Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

where washing is impossible and inspection is difficult. It may evolve as standard operating procedure to cross over small freshwater lakes after traversing the open sea and let the freshwater spray wash the vehicle.

The other major consideration is the behavior of the structural materials at low temperatures. This will be discussed in detail for materials that are considered suitable for marine use.

MATERIALS AT LOW TEMPERATURES

The last decade has seen the development of a multitude of low temperature applications for structural materials. Many of these have been related to aerospace use, particularly the storage and handling of liquid fuels. Because of the need for such fuels, a whole cryogenic industry has developed and structures have been built for their manufacture, storage, transportation, and use. Table 1 lists some of the materials used in these applications. A considerable amount of research has been done on the effect of low temperatures on metal, much of it sponsored by the Government for application in rocket and missile fuel tanks. Generally, the temperatures of interest are the boiling points of liquid oxygen (−297° F), nitrogen (−320° F), and hydrogen (−423° F). Often, however, the mechanical properties of the materials being considered for cryogenic applications are determined at several temperatures between −300° F and room temperature, and curves are drawn between the discrete data points. The data included in this report are interpolated from such curves.

A brief survey of the effects of low temperature on metals is in order before detailed examples of specific alloys are given. These overall concepts become very significant at temperatures considerably lower than those applicable to ASEV operations, but the trends are still evident at the −65° F lower boundary.

As the temperature decreases the strength of most metals increases. The amount of the increase depends primarily on the composition of the metal and/or the crystal structure. Similarly, the ductility and toughness decrease with decreasing temperature. In some cases this decrease can be drastic and may occur over a narrow temperature range.

Metals with a body-centered cubic (bcc) crystal structure (iron and chromium) generally exhibit a loss of toughness over a narrow temperature range. Changes in strength and ductility above and below this transition range are only moderate, but within it the mechanical properties can change dramatically. Above the transition temperature, fracture of the material is ductile and below the range the fracture is brittle. Factors such as grain size, interstitial and alloying elements, inclusions, and notches all affect the temperature range over which the transition occurs. The presence of notches will raise the transition temperature, while certain alloying elements (nickel in iron-base alloys) will lower it, thereby lowering the temperature at which the material will fail in a brittle manner.

The face-centered cubic (fcc) metals (aluminum, copper, and nickel) do not exhibit a transition temperature with the associated large property changes. As the temperature decreases, these metals increase moderately in strength and retain most of their room temperature ductility. It is for this reason that many alloys of this type have been extensively used in cryogenic applications. Another group of materials with the fcc crystal structure is the austenitic nickel-chromium stainless steels. The low temperature effects vary with the specific composition, but several of these austenitic stainless-steel alloys have been used in low temperature service.

The hexagonal close-packed (hcp) metals (titanium, magnesium, and beryllium) behave much like the fcc metals. Yield and ultimate strengths increase considerably as the temperature decreases and ductility decreases only slightly.

TABLE I

MATERIALS IN CRYOGENIC APPLICATIONS

Propellant Tanks for Space Boosters		
Booster	Propellants	Materials
Thor	LOX/RP-1	2014 Aluminum
Atlas	LOX/RP-1	301 Stainless Steel
Titan I	LOX/RP-1	2014 Aluminum
Centaur	LOX/LH_2	301 Stainless Steel
Saturn S-I	LOX/RP-1	2219 Aluminum
Saturn S-II	LOX/LH_2	2014 Aluminum
Saturn S-IV 8	LOX/LH_2	2014 Aluminum

Pressure Vessels			
Vehicle	Contents	Lowest Temperature ° F	Materials
Atlas and Centaur	Helium	-320	Ti-6Al-4V
Saturn S-IV B	Helium	-423	Ti-6Al-4V
Apollo	LOX	-297	Inconel 718
Apollo	LN_2	-320	Ti-6Al-4V
Apollo	LH_2	-423	Ti-5Al-2.5Sn ELI
Lunar Module	LHe	-452	Ti-5Al-2.5Sn ELI

ELI – Extra-low interstitial.

Ductility is not a critical design parameter since design stresses at maximum service load are usually well below the yield strength. Ductility is important, however, from the standpoint of localized deformation during fabrication and any abnormal usage of the structure.

The toughness criteria that are important are those which apply to fracture resistance at pre-existing flaws, cracks, and notches. The effect of temperature on these criteria is well established in a general way, but the whole concept of toughness is far from being fully understood.

For bcc metals, a very narrow temperature range will cause a sharp decrease in impact strength. This transition temperature range is not necessarily the same as the ductility transition since the parameters that identify the phenomena are different. The fcc and hcp metals do not have this sharp toughness drop, but either gradually decrease with temperature or have essentially no change. It is important, however, to realize that the room temperature toughness of these materials is often much lower than bcc metals (e.g., low alloy steels).

There are two distinct ways to measure the toughness of materials. The easier, and more common is the relative measure given by such tests as the Charpy impact, dynamic tear (DT), and notch tensile tests. Less understood tests are the fracture mechanics tests which determine the critical stress intensities (K_{Ic}) and from them critical flaw sizes. Unfortunately, this second approach is only valid in the material's elastic range, and great care must be taken in the interpretation of test results. In addition, the stress environment in service is rarely known well enough to apply fracture mechanics.

For material comparisons, probably the most common toughness test is the Charpy test. There is a large quantity of Charpy test results available over a wide range of temperatures. For materials with large temperature-dependent changes in toughness, this test has proven extremely useful. It can quickly identify transition temperature ranges and eliminate unlikely candidates for a particular application. Another measure of the relative toughness is the notch-to-unnotch tensile-strength ratio. These tests are easy to run on sheet as well as heavy plate but care must be taken when making comparisons between sheet and round tensile specimens. The state of stress is very dependent on the specimen and notch geometry. Also, large changes are seen for the ratio only when there are large temperature changes. The NRL dynamic tear test is also a comparative test, but the specimen is designed to place more of the metal under test under plane strain conditions. Therefore, there has been better correlation with fracture mechanics tests, and empirical relationships between DT results and critical stress intensities are being developed by NRL. These relationships are only valid for certain high strength materials and the data, at present, are limited to 32° F.

The design objective of fracture mechanics testing is to be able to predict the critical flaw size for a given material, at a specific stress level, environment, and temperature. Hopefully, this flaw size would be larger than the minimum detectable, and could be inspected out of the structure. Flaws include such defects as notches, inclusions, voids, etc, that could result from manufacturing or fabrication. In order to determine the critical flaw size, it is necessary to establish the critical stress intensity (K_{Ic}) at the lowest service temperature. In some cases a salt-water environment can have a significant effect, and the resulting "wet K_{Ic}" can be much lower than the "dry K_{Ic}." The specimen design for fracture toughness testing is important and is a function of the strength level of the material. For the predictive relationships to hold, it is essential that the metal under test be in a plane strain condition (no shear stresses or plastic deformation). Therefore, as the strength of the material decreases, the necessary specimen size increases. There are only limited data of this type available at low temperatures but they confirm all the trends shown by the comparative toughness tests.

MATERIAL CHARACTERISTICS

ALUMINUM ALLOYS

Commercial wrought-aluminum alloys can be separated into two categories – the heat-treatable and the nonheat-treatable series. The heat-treatable alloys achieve their strength by precipitation hardening due to a combination of solution annealing, quenching, and aging. The non-heat-treatable alloys are solid-solution strengthened then work hardened to various levels. A uniform numbering system has been adopted for the aluminum alloys based on the major alloying elements. The more common series used in structural applications are the 2XXX series containing copper, the 5XXX with magnesium, the 6XXX with magnesium and silicon, and the 7XXX series in which aluminum is alloyed with zinc. The 5XXX series is the only one of these that is non-heat-treatable. Although the 5XXX series is not as high in strength as some of the heat-treatable alloys, it has much better welding characteristics and corrosion resistance.

Corrosion Characteristics

The 5XXX series alloys are the most widely used in sea-water applications. Alloys 5083, 5086, and 5456 are the highest strength alloys in the series and have general corrosion rates in sea water of about 0.2 mils per year (mpy) (bulk weight corrosion loss). Pitting of these alloys is minimal, typically, 50 mils after a 5-year exposure. For comparison, a 0.250-inch-thick unprotected plate of one of the 7XXX alloys might be perforated after a few years.[5] Corrosion in a marine atmosphere is not significant with the 5XXX alloys. Many ships have superstructures made of these materials. For example the SUNRIP, a bauxite carrier built in 1954, used unpainted 5083 and 5086 which, after a careful examination 10 years later, required no repair due to corrosion damage.[6] Alloy 5456 sheet, plate, and extrusions have been used as deck, side, and bottom plating, frames, girders and bulkheads of several U.S. Navy hydrofoils. This alloy has seen extensive service in small craft such as the PCF ("Swift") boats and other coastal and riverine patrol boats. The only problem encountered was some selective corrosion (exfoliation) on interior surfaces which has been eliminated by the use of a new tempering treatment in manufacture.

The 6XXX alloys are heat-treatable and can be processed to higher strength levels than the 5XXX alloys. The most common alloy used in the United States in this series is 6061-T6. T-6 is the temper designation (solution treated then artificially aged). The corrosion resistance of this alloy series is not as good as the aluminum-magnesium series (5XXX), but they can still be used without protection in marine atmospheres. The 6061 alloy extrusions have better corrosion resistance than plate products, and show a high incidence of pitting, a low rate of penetration, and only a slight tendency for intergranular corrosion.

The 2XXX series should not be used in a marine environment without adequate protection. Under certain conditions of heat treatment, the copper-aluminum microscopic phases segregate to grain boundaries causing the alloy to be extremely susceptible to stress corrosion and intergranular cracking.

The high strength, heat-treatable 7XXX alloys are very similar in behavior to the 2XXX alloys. They should not be used in sea water unless well protected. Because of their grain structure, they are particularly sensitive to stress corrosion in the short transverse (through-the-thickness) direction. However, a few specially developed alloys in the 7XXX series are not susceptible to stress corrosion in sea water.

Welding Characteristics

Since the strength of the heat-treatable alloys depends upon the size and distribution of microconstituents, it is not surprising that welding causes large changes in mechanical properties. All alloys, however, are weldable, with the final strengths being dependent on filler-wire composition and postweld heat treatment.

Welding of the 7XXX series is particularly difficult. There is a tendency to crack unless special precautions are taken for setup, and heat inputs are kept low.

The 2XXX alloys vary in weldability. Alloy 2024 has very limited capacity for welding, and cracking is extensive in some filler metals. Alloy 2014 has better welded characteristics and has been used in missile applications. Alloy 2219 is considered one of the most weldable of the high strength aluminum alloys and is also not particularly sensitive to welding procedure.

The major weldable alloy of the 6XXX series is 6061. A considerable amount of work has been done on the weldability of this alloy, and filler wires, heat inputs, and procedures are well documented. Weld repairs can have an effect on the mechanical

properties, since they represent additional heat inputs. Table 2 shows this effect on 0.125-inch-thick 6061-T6 plate welded by automatic gas tungsten arc (GTA) and gas metal arc (GMA).[7] The 2XXX, 7XXX, and 6XXX alloys all require a postweld heat treatment to return the mechanical properties to near prewelded levels.

TABLE 2

WELDED 6061-T6 STRENGTH

Condition	Tensile Strength ksi	Yield Strength ksi	% Elongation
Control-GTA welded and aged	43.4	38.0	4.8
GTA welded, 1 repair, aged	33.0	27.5	3.2
GTA welded, 2 repairs, aged	32.7	27.1	4.0
Control-GMA welded and aged	42.6	37.4	4.8
GMA welded, 1 repair, aged	36.3	32.4	3.0
GMA welded, 2 repairs, aged	32.7	26.9	3.8

The 5XXX nonheat-treatable alloys are readily weldable and do not require a postweld heat treatment. Joint efficiencies (welded-to-unwelded strength ratios) of 80% to 100% have been achieved with both GMA and GTA procedures. Optimum base-metal/filler-wire combinations have been determined as well as welding procedures for GTA and GMA. Table 3 shows typical welded strengths of the high strength 5XXX series alloys.[8]

TABLE 3

STRENGTH OF 5XXX SERIES ALUMINUM ALLOYS

Base Metal	Filler Wire	Transverse Weld Tensile Strength, ksi
5083	5183	42.5
5086	5183	38.7
5456-H321	5556	50.7

Low Temperature Characteristics

Strength

Table 4 lists the tensile properties of several aluminum alloys at room and low temperatures. As outlined earlier, the 2XXX and 7XXX series are not good candidates for application in a marine environment, but 7075-T6 has been included as representative of the higher strength alloys.

TABLE 4

STRENGTH OF ALUMINUM ALLOYS

Alloy	Temperature ° F	Yield Strength ksi	Tensile Strength ksi	% Elongation
5456-H321	RT	34	51	17
	-65	40	63	24
5083-H113	RT	33	46	16
	-65	37	52	23
5086-H32	RT	30	42	12
	-65	32	47	20
7075-T6	RT	72	82	11
	-65	76	86	13
6061-T6	RT	40	45	12
	-65	43	51	13

RT – Room temperature

The strength increases are all consistent but only marginally improved. The ductility increases with the decrease in temperature. Although the 5456 alloy has the highest strength, the other alloys (5083 and 5086) remain candidates because of differences in fabrication characteristics, which may be important as vehicle design develops. The 6061 alloy may be useful for parts such as engine supports and other high strength applications.

The modulus of elasticity of aluminum alloys is about 10.0×10^6 psi and will increase to about 10.5 to 11×10^6 psi at -65° F. The shear modulus increases by a corresponding amount, indicating that Poisson's ratio is unaffected by temperature.

Toughness

The Charpy V-notch energies and notched tensile ratio data for these aluminum alloys do not vary significantly over the temperature range of interest. Table 5 lists the Charpy impact and notched tensile ratios of various alloys.[9,10]

Data on fracture toughness tests run on several 2XXX and 7XXX alloys indicate that these materials can sustain cracks at low temperatures at least as large as, and generally larger than, those which occur at room temperature.[11] Fracture toughness tests will be run on 5456-H117 (similar mechanical properties to H321, but heat treated to avoid exfoliation). The tests will be primarily of the bent-beam, four-point-load type, and dynamic tear tests.

Fatigue Properties

The structural material of an ASEV will be subjected to fatigue in cold and warm (above 32° F) air and in water (also above 32° F). The effect of cold air on fatigue strength is shown on table 6. In all cases, both welded and base metal, decreasing temperature increases fatigue strength. Thus cold air is not a limiting factor in fatigue design.

TABLE 5

TOUGHNESS OF ALUMINUM ALLOYS

Alloy	Charpy Impact		Notched Tensile Ratio[1]	
	Temperature of Test	Energy ft-lb	Temperature of Test	Ratio
5456-H321	RT	21	–	[2]
	-80	21	–	[2]
5086-H32	RT	22	RT	1.02[3]
	-80	22	-100	1.03[3]
6061-T6	RT	11	RT	1.05
	-80	11	-100	1.02
7079-T6	RT	6	RT	1.08
	-80	6	-100	1.04

(1)Sheet specimens with sharp notch ($k_T > 7$).
(2)Available data inconsistent; will be retested at this laboratory.
(3)H34 Temper.

TABLE 6

FATIGUE STRENGTHS IN AIR OF ALUMINUM ALLOYS

Alloy	Test Temperature ° F	Tensile Strength, ksi	Fatigue Strength, ksi		Reference
			10^6 cycles	10^7 cycles	
5456-H323 Base Metal	RT	56	–	15	12[1]
	-320	–	–	25	12
5456-H323 Weld Metal	RT	56	–	10	12
	-320	–	–	12	12
5456-H321 Base Metal	RT	52	36	–	13[2]
	-320	69	40	–	13
5456-H321 Weld Metal	RT	45	24	–	13
	-320	59	29	–	13
5083-H113 Base Metal	RT	50	35	–	13
	-320	66	40	–	13
5083-H113 Weld Metal	RT	41	22[3]	–	13
	-320	60	28[3]	–	13
6061-T6 Base Metal	RT	45	–	20	14[4]
	-110	52	–	23	14

(1)Axial Tests, R = -1.0.
(2)Axial Tests, R = 0.0.
(3)Estimated.
(4)Rotating beam tests.

The fatigue strengths of aluminum alloys in sea water are, however, much lower than fatigue strengths in air. Table 7 contains data on rotating beam specimens run in salt water at this laboratory.[15]

TABLE 7

ROOM TEMPERATURE CORROSION FATIGUE STRENGTH OF ALUMINUM ALLOYS

Alloy and Temper	Tensile Strength ksi	Fatigue Strength, ksi		
		Air	Salt Water	
		10^8 cycles	10^7 cycles	10^8 cycles
5086-H112	47	18*	6	3
5086-H32	41	22.5	4	2
5456-H321	47	20	5	2
6061-T6	52	16*	7*	4*
7079-T6	73	15*	6	2*

*From extrapolated curve.

As shown above, all the alloys have corrosion fatigue strengths below 8 ksi at 10^7 cycles. These tests were run in water with salt content less than that of sea water. It is possible, under certain conditions, for water in the Arctic to contain more salt than sea water. If the occurrence of this high salinity water is indeed significant, then tests will be run at this laboratory with this new boundary condition.

It is unusual to use aluminum in a marine environment without some form of protective coating. A study by Inglis and Larke[16] has shown that annodizing improves the corrosion fatigue resistance but lowers the fatigue strength in air. Painting has no detrimental effect on the fatigue strength in air (indeed it can actually improve it by excluding the moisture) and eliminates the loss of fatigue strength due to salt water. Obviously the protection is only as good as the coating. It is difficult to foresee sufficient inspection of remotely accessible parts on a large ASEV to have reliance on coating integrity. Thus the design would have to be for corrosion fatigue strengths rather than air or painted fatigue strengths. This matter also applies to most of the steels, where their location prevents proper inspection.

TITANIUM ALLOYS

Titanium alloys are classified into three types according to their room temperature microstructure, which is primarily dependent on amount and type of alloying element. The alpha titanium alloys containing combinations of Al, Sn, and O_2 are low strength, high toughness alloys, easily weldable but often sensitive to stress-corrosion cracking. The near-alpha and alpha-plus-beta alloys containing Al and moderate amounts of V, as well as Cb, Ta, and Mo have a wide range in properties and can therefore be utilized in a variety of applications. The strength and toughness properties can be adjusted by alloy content, and to a certain extent by heat treatment, with accompanying changes in weldability and stress-corrosion sensitivity. The least developed system, the beta alloys, are most sensitive to heat

treatment. With these alloys (which contain little Al and considerable Mo, V, Cr, Cb, and Ta) the matching of welded and baseplate properties is difficult and the sensitivity to stress-corrosion cracking is largely unknown.

All titanium alloys have extremely good resistance to general corrosion, erosion, pitting, and crevice attack. Some alloys are sensitive to stress-corrosion cracking in the presence of a highly stressed flaw, but many alloys are immune to this type of attack.

The main problem associated with titanium alloys is their high reactivity and affinity for oxygen. This means that during the melting, heat treatment, and welding processes the metal must be protected from air. If the metal picks up appreciable oxygen and nitrogen, the strength rises and the material quickly becomes embrittled. This is particularly critical in welding operations and great care must be taken to ensure that the argon or helium gas shield is adequate. Despite these difficulties, welding "out of chamber" is a routine operation for normal configurations. Considerable experience has been gained by the aircraft manufacturers in the fabrication of this alloy system. This experience will be directly applicable to the construction of a large SEV.

The importance of the O_2, C, N, and Fe levels in titanium alloys cannot be overemphasized. In sea water, alloys which are not normally sensitive to stress-corrosion cracking can become so with an increase in oxygen level. This increase could be local (e.g., a faulty spot-weld repair) and could cause failure if located in a high stress area. At low temperatures the effects of these contaminants are more pronounced.

The titanium alloys currently used by the aerospace industries contain from 1600 to 2000 ppm oxygen. This is the normal commercial grade of material. Recognizing the need for higher purity material in certain applications, the titanium industry has produced a grade of alloys with 1200 to 1500 ppm oxygen termed extra-low interstitial. However, for the reasons outlined in the previous paragraph and because of an interest in tough plate products, the Navy has been purchasing titanium alloys at special oxygen level of between 800 to 1000 ppm. At this stage it is believed necessary to maintain the 800 to 1000 ppm requirement for all marine structures. Very few (if any) sheet titanium products have been produced at this low oxygen level; thus, property information on this product form is lacking. Low oxygen plates have been extensively evaluated at room temperature by this laboratory and there is a high degree of confidence in their applicability to marine structures of all kinds.

Low Temperature Properties

As mentioned above, low temperature data on low oxygen titanium alloys is scarce. However, the data on the high oxygen material confirms the expected trends of increasing yield and tensile strengths and low, but relatively constant, toughness values.

The alloys of interest for marine applications are commercially pure (CP) titanium, Ti-6Al-2Cb-1Ta-1Mo and Ti-6Al-4V. The strength and toughness of these alloys in low oxygen plate form is shown in table 8. In thin sheet form these strengths will be raised 15% to 20%.

The notched tensile-strength ratio does not change over temperatures down to -200° F. Fracture toughness data for high oxygen, Ti-6Al-4V, indicates that there is no drop in K_{Ic} values (45 ksi $\sqrt{\text{inch}}$ for 145 ksi yield strength) down to -100° F.[18] Ratio's of K_{Ic}/σ_{ys} of 1.0 have been determined for some of the tougher alloys (e.g., Ti-6Al-2Cb-1Ta-1Mo). However, with these tough materials there is a question about the validity of any K_{Ic} number determined in specimens less than 2 or 3 inches thick.

TABLE 8

STRENGTH AND TOUGHNESS OF 1-INCH-THICK TITANIUM ALLOYS

Alloy	Test Temperature ° F	Yield Strength ksi	Tensile Strength ksi	Charpy Impact ft-lb	Reference
CP	RT	30-50	40-60	100	*
	-65	45-65	55-75	80	*
Ti-6Al-4V	RT	120	132	17	12
	-65	135	148	15	12
Ti-6Al-2Cb-1Ta-1Mo	RT	110	121	36	17
	-65	126	140	23	17
*Estimated					

Fatigue strengths increase with decreasing temperature. Ti-6Al-4V sheet (136 ksi tensile strength) tested in fully reversed flexural fatigue has fatigue strengths at 10^6 cycles of 50 ksi at room temperature and 60 ksi at -110° F. Notched specimens (K_t = 3.1) of the same alloy have fatigue strengths at 10^6 cycles of 25 ksi at room temperature and 35 ksi at -110° F.[12] The corrosion fatigue strength of these three titanium alloys is the same as the fatigue strength in air. The results of room temperature fatigue tests run in air and salt water at this laboratory are listed in table 9.

TABLE 9

ROOM TEMPERATURE FATIGUE STRENGTHS(1)

Alloy	Tensile Strength ksi	Fatigue Strength, ksi			
		Smooth		Notched (K_t = 3)	
		Air	Salt Water	Air	Salt Water
CP	67	26(2)	26(2)	–	–
Ti-6Al-4V	135	55	55	38	35
Ti-6Al-2Cb-1Ta-1Mo	125	38	40	20	20

(1)Rotating beam test, R = -1.0, 1450 cpm.
(2)Data on welded specimens.

The corrosion fatigue strengths of welded Ti-6Al-4V and Ti-6Al-2Cb-1Ta-1Mo are much lower than those of the base metal. A possible solution to this problem is being investigated on another program.

NICKEL ALLOYS

The application of nickel alloys in marine structures has not been extensive. However, the excellent performance of nickel alloys in turbulent and high velocity sea water has long been recognized, and has resulted in the use of nickel-copper alloys for valves and impellers. The performance of nickel alloys in quiet sea water (less than 3 fps velocity) has varied considerably with some alloys reportedly undergoing severe local attacks and others having complete immunity to pitting and crevice corrosion. A thorough study of the corrosion characteristics of 22 nickel alloys has recently been completed by Niederberger, *et al.*[19] After exposure, the various alloys were classified as to type and severity of attack. Three alloys showed no general corrosion and no pitting and crevice attack. Of these alloys (Rene 41, Inconel 625, and Hastelloy C), only Rene 41 had high strength (93 ksi yield in the annealed condition). The four next-best alloys exhibited little or no pitting and only minor attack in crevices, but all had low strength. The next group, those having little or no pitting and moderate to severe crevice attack, contained Inconel 718 and Incoloy 901, which are both high strength alloys. All the remaining alloys tested had increasingly severe corrosion susceptibility and were for the most part low in strength. None of the alloys were susceptible to stress-corrosion cracking based on a U-bend test; however, further studies should be made with the cantilever beam and other tests.

The major problem with all of these precipitation-hardened nickel alloys is welding.[20, 21] Two types of cracking can occur during the welding process and while methods for avoiding them are being investigated, further work to establish detailed procedures will be essential, if the high strength nickel alloys remain ASEV structural candidate materials. The two types of cracking are microfissuring of the root passes during welding, and strain-age cracking during the postweld heat treatment. Porosity, lack of fusion, and hot cracking can also be encountered unless special precautions are taken.

The two most promising nickel alloys are Inconel 718 and Rene 41. More information is available for Inconel 718, but mechanical property determination of both base metal and welded Rene 41 is under way on another program. Because of the difficulties of welding outlined in the previous paragraph, several postweld treatments will be evaluated. Generally speaking, Inconel 718 is much easier to weld (less subject to strain-age cracking) but more sensitive to pitting and crevice corrosion. The strength properties are higher (150 to 170 ksi yield for Inconel 718 compared to 100 to 130 ksi yield for Rene 41), although exact levels obtainable after welding are not definitely known.

Low Temperature Properties

The high strength nickel alloys achieve their strength by a combination of solid solution strengthening and precipitation hardening. Thus, properties at a given temperature will vary considerably, depending on the thermal treatment given to the material in test. The strength data reported in table 10 shows results of tests on material in the annealed and fully aged conditions.[22]

The increases in strength at −65° F are not large but are consistent for all heat treatments. The ductility is practically unchanged over this same temperature range.

The notch strength ratios at room temperature and −65° F of these two alloys are either the same at the two temperatures, or only slightly lower at −65° F. The form of material (sheet plate, bar, etc) will affect the test results slightly. Single-edge notched specimens were used to determine the K_{Ic} values of welded Inconel 718 sheet.[23] The results showed some scatter which may have been due to welding defects, but the data all increased with decreasing temperature. The room temperature K_{Ic} values of 30 to 55 ksi $\sqrt{\text{inch}}$ increased to 40 to 65 ksi $\sqrt{\text{inch}}$ at −320° F, and 55 to 80 ksi $\sqrt{\text{inch}}$ at −423° F.

TABLE 10

STRENGTH OF NICKEL ALLOYS

Alloy	Heat Treatment	Yield Strength ksi		Tensile Strength ksi		% Elongation	
		-65° F	RT	-65° F	RT	-65° F	RT
Inconel 718	1950° F & Aged	169	158	194	182	27	28
	1800° F & Aged	160	155	192	187	29	30
Rene 41	Solution Anneal	85	73	147	135	49	45
	Solution Anneal & Aged	150	140	200	190	14	15

The fatigue data on Inconel 718 at low temperatures is not entirely consistent. In one case, the -320° F fatigue strength at 10^6 cycles is below that of room temperature tests. For the same conditions though, the -423° F data are considerably higher than the room temperature data. The welded specimen data show the normal increasing fatigue strength with decreasing temperature. The fatigue strength of Inconel 718 in sea water is about 20 to 25 ksi at 10^8 cycles.

STEELS

Of the many classes of steels, those most applicable to an ASEV structure are the austenitic stainless steels, precipitation-hardened stainless steels, and the martensitic steels. Most of these steels are either fcc (and do not have a ductile-brittle transition) or are bcc with a very low temperature transition. There are some specialty steels, such as the 9 Ni steel, which may also be appropriate. The quench and tempered steels are not good candidates because of their poor low temperature properties and poor corrosion characteristics.

Austenitic Stainless Steels

The AISI 300 series contains about 18% chromium and 8% nickel which stabilize the fcc austenite at room temperature. These steels cannot be strengthened by heat treatment but are strengthened by cold working. They are readily weldable and do not require postweld heat treatment. As a group, their general marine corrosion is good, and type 316 is one of the best. However, this steel has not had wide application in marine structures because of its poor crevice corrosion resistance. Also, its relatively low strength makes it unattractive as a structural material on a weight-critical craft. Its properties are listed in tables 11 and 12.

Precipitation-Hardened Stainless Steels

These steels can be of either an austenitic or martensitic type and require heat treatment to develop high strength. The alloys are not work hardenable to any great extent and may require postweld heat treatment. The most common alloys of this type are 17-4 PH and A286. The general corrosion resistance of 17-4 PH is excellent although pitting and crevice corrosion in localized areas is severe. This would probably not be a serious problem in an ASEV.

TABLE 11

ROOM AND LOW TEMPERATURE STRENGTHS OF SELECTED STEEL ALLOYS[22, 24-27]

Alloy	Condition	Tensile Strength ksi		Yield Strength ksi		% Elongation	
		RT	-65° F	RT	-65° F	RT	-65° F
316 stainless	–	80	100	45	–	80	80
17-4 PH	H1100	187	205	180	190	15	15
A286	STA[1]	160	170	100	103	15	15
9Ni-4Co	STA	201	225	178	185	18	18
18 Ni (marage)	250 grade	255	275	250	265	3	2
	180 grade	190	205	180	195	3	2
9 Ni	N+SR[2]	135	145	100	105	22	22

(1)STA – Solution treated and annealed.
(2)N+SR – Normalized and stress relieved.

TABLE 12

RELATIVE TOUGHNESS OF STEELS[22, 24-27]

Alloy	Notched Tensile-Strength Ratio		Charpy Impact	
	RT	-65° F	RT	-65° F
316 stainless	1.20	1.18	135	132
17-4 PH	–	–	55	22
A286	1.0	0.95	65	65
9Ni-4Co	1.0	1.0	65	65
18 Ni (marage) 250 grade	1.10	1.08	23	23
180 grade	–	–	55	49
9 Ni	–	–	95	85

Martensitic Steels

Dual Strengthened Steels

The purpose of the development in steels of this category was to combine the strenthening effect of carbon martensite and age hardening. The weld metal would presumably have the high strengths associated with martensitic formation, which upon tempering due to multipass welding, would match baseplate properties. The two steels developed in this class were 10Ni-8Co-2Cr-1Mo and 9Ni-4Co-0.2C. Good weldments have been achieved with both hot and cold wire GTA weldments, without postweld heat treatments, but deposition rates are extremely slow.

Age Hardenable (Maraging) Steels

The two primary steels in this category are the 12 Ni and 18 Ni maraging steels. The 18 Ni steel has better toughness in the base metal, but the weld metal of both steels is susceptible to stress-corrosion cracking in sea water. Gross, *et al*,[24] concluded that this corrosion problem eliminated these steels as candidates for HY 180/210 structural application in the Navy. Certain limited applications could be possible for this material in an ASEV if due consideration is given to inspection and maintenance of a coated surface.

Other Steels

Several other steel alloys have been used for cryogenic applications, particularly a 9% Ni steel (2800) which was developed specifically for use in low temperature storage vessels. This alloy exhibits a gradual transition behavior, however, between -50° and -250° F.

The strength and elongations of the steel alloys discussed above are listed in table 11. These strengths should be considered typical and not used for detailed design purposes. The notched tensile-strength ratios and Charpy impact values are shown in table 12.

As shown in table 12, there is no loss of toughness at -65° F with these steels, with the exception of 17-4 PH. This alloy has a martensitic base which accounts for its drop in toughness.

Where fatigue data are available for these alloys at low temperature, they indicate that the usual trends are followed. For example A286 welded specimens (solution-treated condition, axial loading, R = -1) had fatigue strengths at 10^6 cycles of 18 ksi at room temperature, 20 ksi at -320° F, and 32 ksi at -423° F. As with the other materials, however, the limiting condition for fatigue is the corrosion fatigue strength in sea water. In this environment, the high strength steel alloys (9Ni-4Co, 18 Ni maraging) have fatigue strengths of less than 10 ksi at 10^8 cycles.[24] The stainless alloys are slightly better, with 17-4 PH and 316 stainless steel having values as high as 20 ksi at 10^8 cycles.

STRUCTURAL PLASTICS

Background

Glass-reinforced plastics (GRP) are a class of materials having a unique combination of properties which make them particularly adaptable for marine structural use, including structural applications for the ASEV. These materials are high in strength, low in weight (1/4 the weight of steel), inherently resistant to corrosion and are nonmagnetic. They are readily fabricated into large complex shapes and can be tailor-made for particular applications, in that properties may be varied at the discretion of the designer.

In the present state of the art, GRP refers to a variety of materials, ranging from low glass content mat-reinforced polyesters for applications where low strength may be adequate, to high strength, filament-wound, glass-reinforced epoxy laminates, where a high stiffness-to-weight ratio is required.

Composites can be fabricated with tensile strength varying from 20,000 to 150,000 psi and moduli from 1.0 to 9.0 million psi. The above indicated flexibility in properties is available to the engineer and is one of the principal advantages of GRP to the designer.

These materials have been used extensively in marine applications, particularly in small boats. Other naval applications have been: sonar domes, minesweeping devices, radar masts, deckhouses, and submarine fairwaters. The latter has resulted in one of the most successful applications of GRP materials to date. Fried and Graner[28] show that, after 11 years of actual service, a GRP fairwater aboard the submarine USS HALFBEAK suffered no loss in mechanical strength due to exposure in the marine environment. It has been demonstrated[29] that, after 5 years immersion in sea water, a glass-reinforced laminate retained over 95% of its original strength and stiffness characteristics.

Recently, a midship section of a minesweeper was fabricated and subjected to underwater explosions at UERD, Norfolk. The midship section was made of a glass-reinforced polyester material which was layed up in a female mold. The section was 34 feet long, 25 feet deep, and 28 feet across the beam; the weight was 40 tons. This represents the largest GRP structure manufactured to date in the United States. There are indications on the basis of a visual inspection that the GRP hull laminate was not adversely affected by the underwater explosions. However, there were some areas of delamination in the secondary bonds of the joints between the transverse stiffeners and the hull plating.

In addition to being exposed to the marine environment, it can be expected that these materials will be subjected to weathering for extended periods. A number of investigations[30, 31] on the effects of weather aging on GRP materials have been carried out. It has been found that, although these materials may be subjected to different climates, their properties are not seriously affected by long-term exposure to the weather. In general, mechanical properties of GRP materials are normally enhanced as the temperature decreases.

Recent advances in fiber technology have led to the development of high modulus carbon and boron fibers. A comparison of currently available fibrous reinforcements appears in table 13. The high modulus fibers offer filament-wound materials with enhanced compressive modulus. A discussion of the properties attainable with carbon fiber epoxies[32] shows that compressive strengths of 150,000 psi and a modulus of 25 million psi can be achieved with this type material.

TABLE 13

PROPERTIES OF CURRENTLY AVAILABLE FIBROUS REINFORCEMENTS

Fiber	Density lb/in^3	Tensile Strength, psi	Tensile Modulus, psi
E-glass	0.092	250,000	10×10^6
S-glass	0.092	700,000	12×10^6
Boron	0.092	300,000	60×10^6
Carbon	0.063-0.072	200,000-450,000	$25-60 \times 10^6$

A detailed discussion of the currently available types of reinforced plast'c materials, i.e., glass-woven fabric laminates, nonwoven (filament-wound) glass laminates, and carbon or boron composites follows. Included is a discussion of their properties, fabrication procedures, and cost.

Glass Fabric Reinforced Laminates

Resin Type

Glass-reinforced plastic laminates are normally fabricated either with polyester or with epoxy resins. The former, because of its capability of curing at room temperature and ease of handling, is the resin most frequently used. The epoxy resin system does not lend itself to room temperature cure; for optimum properties the cure must be effected under heat and pressure.

Reinforcement

In general, a glass reinforcement is normally used; it can vary from a chopped fiber mat through a woven reinforcement to a nonwoven directional fiber. The amount and type of glass, fiber orientation, and quality of laminate dictates the properties attainable.

Composite Properties

Composites fabricated with a random fiber chopped-mat material as the reinforcement have the lowest strength and stiffness properties. Strength and stiffness values of the composite may be increased by using different grades of woven fiber reinforcements, with the highest strengths normally attained with a woven fiber-reinforced epoxy laminate. Table 14 illustrates the range of values available through the use of different types of glass reinforcement.

TABLE 14

COMPOSITE PROPERTIES

Property	Chopped-Mat Laminate	Woven Fabric Laminate
Specific gravity	1.3	1.7
Tensile strength, psi	20,000	70,000
Compressive strength, psi	15,000	40,000
Modulus of elasticity, psi	1.0×10^6	3.0×10^6

Fabrication

Most structures are normally fabricated with a polyester resin either by hand lay-up or by a spray technique (the latter is the least expensive method). If a higher quality structure is required, fabrication is accomplished by vacuum bag molding. The most expensive method, but one which produces the highest quality laminate, is the fabrication of a glass-epoxy resin composite in a closed mold under heat and pressure.

Cost

Cost considerations for all laminates are confined only to raw materials; no estimate is made of fabrication costs. For the glass fiber laminates, costs can vary from 40 to 80 cents/pound depending on the type of glass and resin system used. A random-fiber chopped-mat polyester laminate is the least expensive while a woven fiber-epoxy laminate, which is fabricated in a mold and cured under heat and pressure, is the most expensive material.

Low Temperature Properties

The properties at low temperatures of GRP laminates are influenced by many factors; i.e. type of resin, degree of cure, curing temperature, and hardener system, among others. In general, it appears that the strength and stiffness characteristics of fiber-reinforced plastics increase with decreasing temperature. A woven fabric polyester laminate[33] tested at -65° F shows an increase of 23% in tensile strength (from 53,000 to 65,000 psi) and an increase of 12% in flexural strength (from 65,000 to 73,000 psi). Similarly, the stiffness characteristics of polyester materials increase with decreasing temperature. Bair[34] reports that the tensile modulus for a woven fabric polyester laminate increased from 2.97×10^6 to 3.24×10^6 psi when the test temperature was lowered from 70° to -110° F. Schwartzberg[35] reports similar increases in strength and stiffness of polyester laminates and also for woven fabric epoxy laminates.

Glass-fiber-reinforced materials[36] exhibit increases in impact strength at decreasing temperatures. However, it is to be noted that the impact strength of plastics is determined by the Izod impact method, which cannot be directly related to design criteria.

Glass-Fiber-Reinforced Filament-Wound Plastic (FWP) Composites

These composites exhibit the highest strength and lowest weight characteristics of current composite technology. On this basis, these materials have been prime candidates for the development of pressure hulls for deep diving submersible applications. Their ability to have their fibers aligned in any angle or orientation required to satisfy design criteria is one of their outstanding characteristics.

Resin Type

FWP composites are normally impregnated with an epoxy-type resin system which exhibits high strength when cured under heat and pressure. However, if the new high performance epoxy resins are used in FWP, it has been found that the compressive strength is increased by 28% and the compressive modulus by 15%.[37] A comparison of properties attainable in FWP composites is shown in table 15.

TABLE 15

PROPERTIES OF FWP COMPOSITES

Property	Conventional[1] Epoxy Resin	High Performance[2] Epoxy Resin
Compressive strength, psi	170,000	217,000
Compressive modulus, psi x 10^6	6.5	7.5

[1]Shell 58:68R resin system.
[2]Union Carbide ERLA-0400 resin system.

Reinforcement

The reinforcement is a glass unidirectional fiber in which a number of glass fibers are axially aligned to form a roving. Here, also, the type of glass dictates the properties of the final composite. In general, two types of glass rovings are available, an E-glass material and an S-glass fiber which has the highest strength and stiffness of the two materials. Comparative properties of the two glass systems are presented in table 16.

TABLE 16

PROPERTIES OF GLASS SYSTEMS

Property	E-glass	S-glass
Modulus of elasticity, psi	10×10^6	12×10^6
Tensile strength, psi	500,000	700,000

Composite Properties

FWP composites, in common with other fiber-reinforced plastics, may be designed to have strength and stiffness characteristics which can be made to vary over a wide range of values, depending on the amount and type of glass, orientation of glass, and resin system used.[38] The composite with the highest strength and stiffness is one in which the S-glass fibers are aligned axially (unidirectional composite) and which contains about 80% fiber by weight. However, this type construction has very low strength in the transverse direction. Properties of a 2:1 orthogonal FWP composite (twice as many fibers aligned in one direction as in the opposite direction), and the effects of long-term water absorption and response of material to dynamic and static strengths are described by Fried.[39] A summary of properties attainable on various fiber configurations is given in table 17.

TABLE 17

CONFIGURATION PROPERTIES

Property	E-glass		S-glass Orthogonal	
	Unidirectional	Crossply	58:68 Resin	0400 Resin
Compressive strength, psi	120,000	77,000	170,000	217,000
Compressive modulus, psi	5.8×10^6	3.7×10^6	6.5×10^6	7.5×10^6
Tensile strength	160,000	75,000	–	–

Fabrication

Composites can be readily fabricated by drawing the glass fibers through a resin bath or by using fibers which have been previously impregnated with resin and winding them over

a mold of the desired configuration. If directionality is required, the fibers may be placed where they are required. On completion of the molding cycle, the entire assembly is cured in a press under heat and pressure.

Cost

Ultimate cost of these materials is dependent on the type of glass and resin system used. An E-glass roving with a conventional epoxy system will cost about $3.00 per pound whereas an S-glass roving impregnated with a high performance resin system will cost about $10.00-$15.00 per pound.

Low Temperature Properties

In general, the FWP materials respond much like the glass fabric-reinforced laminates to low temperature environment; i.e., as the temperature decreases, the strength and stiffness characteristics increase. Schwartzberg[35] reports that the tensile strength of a FWP composite increased from 4.2×10^6 psi at 75° F to 4.8×10^6 psi at -65° F. It is also reported that the fatigue strength of these materials increases at the lower temperatures.

Carbon and Boron Fiber Epoxy Composites

The recent development of carbon and boron fibers has introduced filamentary materials with high specific stiffness, in excess of five times that of metals. In areas where the structure would be stiffness critical, these composites would afford the designer a material whose modulus can be varied from 10 to 30 million psi. This can be accomplished by variations in the amount of fiber and/or fiber orientation.

Resin Type

The FWP composites are impregnated with epoxy-type resins which develop optimum properties when cured under heat and pressure. The strength and stiffness of the composite are dependent upon the type of epoxy used, as discussed in the section on filament-wound plastic composites.

Reinforcement

Carbon fibers are prepared by the pyrolysis of rayon fibers, and have a range of modulus from 25 to 60 million psi. They have a nominal diameter of 0.0004 inch and a low density (0.063 pounds/cubic inch). Boron fibers are prepared by the deposition of boron on a tungsten substrate and have a modulus of 60 million psi; fiber diameter is 0.005 inch, and the density is of 0.092 pounds/cubic inch. Boron fibers cannot be bent around a radius less that 6 inches; carbon fibers can be bent around smaller radii.

Properties

Unidirectional composites fabricated with carbon fibers have attained compressive strengths on the order of 150,000 psi and a modulus of 30×10^6 psi.[32] Composites fabricated with this type of fiber have highly directional properties; highest strength is measured parallel to the reinforcing fibers and can be 10 to 15 times the transverse strength. Composites whose modulus varies from 10 to 30 million psi can be fabricated by combinations of carbon and glass fibers in an epoxy resin.[40]

Fabrication

These materials can be fabricated by conventional winding methods over a mandrel and require cure by heat and pressure for optimum properties.

Cost

The current price of carbon and boron fibers is about $250.00 per pound. However, it is estimated that the price of carbon fibers will be on the order of $20.00-$50.00 per pound in 2 to 3 years, and that of boron about $50.00-$100.00 in this time frame.

Low Temperature Properties

Although little effort has been devoted to investigation of the response of these materials to low temperatures, it is anticipated that their strength and stiffness characteristics will likewise improve with decreasing temperature.

COST CONSIDERATIONS

The mechanical properties, as outlined previously in this report, are obviously the most important factors to consider in the selection of candidate materials for the ASEV. However, another extremely important factor is overall lifetime cost of the material as used in this application, including initial material, fabrication, and repair and maintenance costs. Until the ASEV evolves beyond the conceptual stage, it is possible to deal with the cost factor in only a very general manner. The present status of relative cost factors, with respect to the four candidate alloy systems and structural plastics, is discussed below with the metals considered in the order of increasing cost.

ALUMINUM

Aluminum alloys have had a long history of applications in weight-critical structures. Marine alloys with moderate strength have been developed. With this development has come the availability of a large variety of structural shapes, the refinement of welding and joining techniques, and the confidence in the use of these alloys in extremely harsh environments. Costs of aluminum alloys are low, and machining is easy and inexpensive compared to other alloy systems. The aluminum alloys (particularly 5456-H116 or H117) are the most likely metallic candidates for the ASEV structure. The principal disadvantage is low strength. The effect of this strength disadvantage on vehicle design and performance will have to be thoroughly evaluated.

STEEL

Steels will vary in cost, depending on the alloy under consideration. Some steels (e.g., the 300 series stainless steels and the 9 Ni alloy) have been in general use in certain corrosive environments for many years. The technology for the use of these alloys is well developed; consequently costs are low and a variety of product forms is available. Other steel alloys, particularly the high strength alloys (10Ni-2Cr-1Mo-8Co) are relatively undeveloped and will be expensive to buy, machine, and fabricate. It is anticipated that the steels will find their best application in the structural hard points of an ASEV. Such items as engine mounts, nacelle supports, large structural forgings, etc, may require the high strength and high modulus of elasticity of the high strength steels. Disadvantages in the use of the steels include the weight penalty and only fair corrosion resistance.

NICKEL

The nickel alloys have been used as sheet and forgings in limited missile applications. Welding procedures for these alloys are critical and require considerably greater care, with consequent greater expense, than even the specialty steels. Many product forms of the nickel alloys are not off-the-shelf items and although they are available on special order, an allowance must be made for lead time in delivery. If a requirement exists for high strength and good corrosion resistance (perhaps the vehicle underside or the subsystem of gas-turbine engine), one of the nickel alloys should be considered. Rene 41 is completely immune to corrosion in sea water. It is, however, very difficult to machine and consequently fabrication would be very expensive.

TITANIUM

The technological status of titanium alloys is very similar to that of the nickel alloys. The technology exists for the use of titanium alloys, but the application volume has not expanded to the point where costs have reached their minimum or where they are competitive with aluminum or steel. Titanium welding operations require complete protection from the atmosphere which makes the setup critical and welder training costs high. Structural shapes are available as standard product forms but are expensive because of limited demand. Perhaps the best application of titanium alloys would be in the main structural beams of the craft where the high strength-to-weight ratio would be of greatest benefit. Also, if the vehicle skin were designed to carry a significant portion of the load, titanium would be the best material. Vehicle undersides and those portions of the craft in frequent contact with sea water could utilize the excellent sea-water immunity of titanium.

STRUCTURAL PLASTICS

As indicated earlier, the glass-fabric-reinforced laminates have seen considerable marine service. Raw material costs are similar to aluminum alloys and the low strength steel alloys (about 50 cents/pound) but fabrication costs will vary greatly. For reproducible simple shapes, the GRP manufacturing costs are extremely low; whereas, in the complex one-of-a-kind configurations, the necessary hand lay-up techniques are expensive.

Generalizations concerning the cost of using the glass FWP composites are very difficult. If the lower strength, lower modulus E-glass is adequate for an easily fabricated part, then the total cost would probably be less than a comparable titanium or nickel alloy part. If, however, the part is hard to fabricate or requires the properties of S-glass then the use of a metal alloy would be indicated on a cost basis.

The carbon and boron fiber epoxy composites are extremely expensive and would only be used in limited applications that take advantage of their high modulus. For example, extremely high stiffness might be required for a few critical spars, or on an extended mount for a height sensor, etc. These materials have also found limited application as tapes that are bonded to a metal part, thereby increasing the effective modulus of the part.

Materials selection for a vehicle or any portion of it should be based on the performance of a series of parametric analyses. To do this, the vehicle design must have progressed to the point where the effect of a particular material on cost, weight, and performance can be determined. Although it may not be possible to obtain absolute values, relative effects should be apparent before a final material choice is made.

UNRESOLVED MATERIALS PROBLEMS IMPOSED BY THE ARCTIC ENVIRONMENT

METALS

Corrosion and Erosion Effects

It is known that the corrosion process is reduced by low temperatures. However, other aspects of the arctic environment and the operational requirements for the ASEV raise some questions as to the corrosion and erosion effect on ASEV structural materials. It is known that the craft will operate over the open ocean, and therefore, the materials of construction must be resistant to general marine corrosion. It will also operate over fresh water, an environment much less corrosive than sea water. However, a more detailed analysis should be made to determine if any special effects might result from this alternating freshwater/salt-water operation. There is also the possibility of encountering an environment with salt content greater than that of normal sea water. Brine normally leaches from fresh sea ice, resulting over the years in ice with less and less salt content. It is possible, under certain melting conditions, for brine to collect in large sheets on the surface of the ice. An attempt should be made to ascertain the extent and frequency of this standing brine in the arctic environment.

Aluminum alloys are relatively soft and will be very susceptible to erosion by blowing ice and snow particles as well as sea spray. Protective coatings may serve as a remedy for this problem. However, the severity of the problem is unknown at this time, and a method should be devised to evaluate the potential erosion problem. Data on sand and rain erosion may have some relationship to the arctic problem, but rain particles are not as hard and sand particles are probably not as large and do not fly as far off the ground as ice needles.

Particular attention must be paid in the detailed design of the ASEV to avoid areas where water can collect and remain. This is not only necessary to avoid crevice corrosion and pitting attack, but it is also necessary to avoid serious galvanic effects if there are dissimilar metals in the area (e.g., a bolt in a spar of a different metal). Also, if hollow-core extrusions are used in the construction of a craft, provisions for drain holes should be made since any entrapped water might remain undetected indefinitely.

Structural Integrity and Repair Considerations

Differences in thermal expansion coefficients of metals should be taken into account but should not be considered a problem. It is a matter of judicious design and experiments should be planned by design experts to gain familiarity and experience with the behavior. The coefficient data are well documented in the handbooks, and it is not anticipated that any determinations will have to be made. The effect will be particularly important in the vicinity of the engine and other heat sources. If differences in thermal expansion are not taken into account, it is possible that thermal fatigue could occur as the result of differential expansion and lead to the initiation and growth of a crack.

There is potential danger of damage occurring because of the freezing and expansion of water in restricted areas. This would become a repetitive or cyclic action as the craft travels between warm and cold environments. Joints of all kinds are susceptible to this type of damage as are the window and door seals, etc. The spaces between rivets and sheets, between nuts, bolts, and washers, and even certain types of weld joints could be a problem. Experiments in this area are planned for the coming year.

Some provisions for repair must be carried on board the craft. The damage caused by striking an ice ridge may only be slight, but the effect on the craft may be serious.

Temporary repairs to at least the outer structure should be feasible with on-board facilities. This implies the provision of certain basic sheet metal tools such as drills, riveters, cutters, etc, but not welding equipment. It should be possible, despite the adverse conditions, to cut, drill, and either bolt or rivet sections of metal together. Experiments are planned with portable equipment to try to perform some of these tasks under simulated arctic conditions (cold and dark). The information gained in these experiments should give an indication of the extent of repairs possible under arctic conditions.

STRUCTURAL PLASTICS

The survey of the effects of low temperature on the properties of fiber-reinforced plastics indicates that the strength and stiffness characteristics of these materials increases as the temperature decreases. However, it is to be noted that, for the most part, the low temperature characteristics have been generated on materials that are no longer commercially available. It is for this reason that the initial future effort should be to determine the strength characteristics of candidate structural fiber-reinforced plastic materials at low temperatures; this and other areas of effort are described below.

Low Temperature Characteristics

- Determine static strength and stiffness characteristics of candidate materials at low temperatures.

- Develop design criteria on the effect of resin content on strength characteristics, likewise.

- Determine and correlate, as well, the effect of voids on strength and stiffness properties.

Thermal Cycling

It may be expected that the vehicle will be subjected to the following conditions: (1) prolonged exposure to low temperature while in operation, and (2) intermittent exposure to normal temperatures while in a hangar for storage or repair. In this area the following effort should be undertaken:

- Develop information on the effect of thermal cycling (70° to −65° F) on strength and stiffness characteristics.

- Determine the effect on materials properties of storage in water, subsequent exposure to freezing temperatures, and then exposure to normal temperatures.

Repair

Conventional repair procedures for GRP materials have been developed by the Navy. Kits for effecting the repair are normally supplied with a room temperature cure epoxy resin. However, information is required on methods of effecting repairs at low temperatures. Needed areas of effort in this respect include:

- Develop strength characteristics of adhesive and mechanical bonded joints.

- Determine effect of static and dynamic fatigue on varying joint designs.

- Develop design criteria of low temperature effects on static and dynamic strength characteristics of joints.

- Determine effect of thermal cycling on joints.

Static and Dynamic Fatigue

Initiate a program to determine the effects of low temperature on stress rupture (static fatigue) and dynamic loading of fiber-reinforced composites subjected to the arctic environment.

Quality Assurance Acceptance Criteria

- Develop quality assurance procedures with emphasis on nondestructive evaluation (NDE) and processing procedures for material quality control.

- Develop a relationship between strength and stiffness properties with NDE for optimization of construction of structural plastics materials.

SUMMARY

The consideration of candidate structural materials for a craft that has not been designed necessitates the use of a number of generalizations. The performance envelope and operating environment are well enough established to broadly define the boundary conditions, but obviously a large number of tradeoffs will have to be made after design details are established. Within these limitations the following conclusions can be drawn:

- Low temperature toughness is not a problem for the general classes of materials considered in this report. These materials have crystal structures that are either fcc (aluminum, nickel, and austenitic stainless steels), hcp (titanium), or amorphous (the structural plastics). Although these materials do not have high toughness at room temperature, they do not exhibit any significant loss of toughness at -65° F.

- Strength and modulus values increase with decreasing temperature. The increase in strength in most cases is about 10% at -65° F as compared to room temperature, and the increase in modulus is usually less than that.

- The fatigue strength of specimens run in air increases with decreasing temperature. The change is often very small, but in no case is there a decrease in strength. The sea-water corrosion fatigue strength of aluminum and steel alloys is very poor, usually less than about 5 to 10 ksi at 10^8 cycles. This strongly suggests the use of coatings with their attendant penalties in weight and maintenance. Nickel, titanium, and the structural plastics do not suffer from reduced fatigue strength in water.

- The fabrication and repair of vehicles built with aluminum, low strength steels, and GRP materials are roughly comparable and considerably easier (and less expensive) than the higher strength materials.

- The most critical operating environment from the structural materials point of view would appear to be the summer open-ocean condition. At low temperatures strength increases, and in operation over land corrosion is probably not a significant factor.

- Based on information currently available, it would seem that the craft would primarily be constructed of a 5XXX series aluminum alloy with the high strength main structural beams being made of titanium or possibly a nickel alloy. This would mean that conventional fabrication methods could be used and development costs would be low.

Naturally, the design strengths of the components determine the material selections. The above statements presuppose the use of the conventional box beam and spar or extruded-shape type of construction that has been used in SEV craft to the present. GRP materials might be best applied in appendages, tanks, and other nonstructural components.

- Structural material problem areas that need further resolution are corrosion and erosion, repairability, structural integrity (particularly at joints and seals), and determination of some basic material properties (particularly in the structural plastics).

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Appendix A

Annotated Bibliography of Selected SEV References

A literature search revealed a number of potentially interesting documents relating to the design and construction of surface effect vehicles. However, with a few exceptions they were not particularly applicable since the size of the crafts being reported were, for the most part, much smaller than the projected ASEV. Also, the information being sought (details of construction methods) was usually not included in the report.

1. Tachmindji, A. J., "**Surface Effects Vehicle Summer Study**," Study S-349, IDA Log HQ69-10376, Vol. 2 (Oct 1969)

A series of studies on general characteristics of surface effects vehicles. Topics include materials and structures, performance improvement, power and propulsion, obstacle clearing, use of wings, experimental techniques and an R&D program for postulated application. The materials section contains a study on low structural weight fraction justifications. The R&D section contains some general areas needing development for arctic operation.

2. Rochford, C. E., "**Foreign Ground Effect Machines**," U.S. Army Transportation Intelligence Agency, Arlington, Va. (Dec 1961)

Basic design concepts and developments in several foreign nations. The emphasis is on appearance and requirements for the ground effect machines.

3. Lekaron, A. D., "*Structural Design Study of a Ground Effect Machine for Amphibious Support*," Ryan Aeronautical Co. Rept 62B009, San Diego, Calif. (Feb 1962)

This report includes descriptive text, structural drawings, analysis, and criteria of a 62,000-pound gross-weight vehicle. The material survey resulted in the choice of the aluminum alloy 6061 for the vehicle structure (over fiber glass and steel). All component analysis and sizing was based on alloy 6061 properties. A stress analysis for the primary structural beams and skin, the secondary structure pilot house doors and fuel tanks, and the propulsion system. A vehicle weight analysis for all systems of both the 62,000-pound vehicle and similar 90,000 gross-weight vehicle. Resistance welding and riveting are recommended as fabrication techniques.

4. Lambermont, P., "*Bertin Develops a 1000-Ton Marine Air Cushion Vehicle*," **Air and Cosmos**, No. 306, p. 29, (Sep 1969) (Translation).

This article outlines a proposal for a strictly marine craft with transoceanic capabilities. There are drawings and a list of characteristics (speed, power, and dimensions). Rigid or semirigid side walls are favored.

5. Smith, H. A., "*French Air Cushion Vehicles*," ONR London Memo M-2-69 (Jan 1969)

This is a trip report of a visit to the offices of SEDAM Air Cushion Vehicle (ACV) Company. The discussion mentions a 27-ton craft, a 3½-ton craft, and a proposed 200-ton craft which is being designed. A brief description, capabilities, cost, and intended purpose of these craft for land and sea transportation is included.

6. Whittenbury, C. G., "*Ground Effect Vehicles in Overland Operations. Land Combat System – 90*," U.S. Army Advanced Material Concepts Agency, Rept AMCA-70-005, Washington, D.C. (Mar 1970)

This paper outlines individual configuration and performance characteristics at present and predicted for 1990. The required areas for research and development effort are cushion systems, control, power transmission, structures, and propulsion. The emphasis is toward lightweight materials and investigation of glass reinforced plastics (for cutting cost).

7. Mankuta, H., "*Ground Effect Machines Morphology Study*," Bell Aerosystems Co. Rept 2017-945002 (Jan 1961)

Designs are investigated for five vehicles with specific mission requirements. The gross weights of these vehicles range from 2 tons for the 24-foot reconnaissance car to 35 tons for the 75-foot utility barge. A method is developed for selecting size, weight, or power for various size vehicles based on a separate propulsion system. Included is 1-page discussion of materials (steel, aluminum, and wood) for primary structural use. Detailed structural design of each vehicle would be required before material selection.

8. "*Trials of an SR-N5 Hovercraft in N. Canada*," Defense Research Board, Canada, Rept DR 182 (Oct 1966)

This report describes tests conducted during 71 hours of operation in temperatures ranging from −24° to 60° F over sea ice, pressure ridges, and open water. All phases of operation, maintenance, and design are detailed. No problems were encountered with maintenance and serviceability except with skirt wear. Repairs were performed in the field successfully at 20° F. The craft performance is evaluated with respect to terrain crossing ability, meteorological limitations, range, and endurance.

9. Brown, A. J., "*SK-5 Air Cushion Vehicle*," U.S. Army Combat Developments Command Trip Rept 39-68, APO San Francisco, Calif. (15 Aug 1968)

The report is specifically aimed at evaluating the ACV as a combat vehicle in Vietnam. The report considers a platoon of three vehicles utilized with various types of units such as infantry, light artillery, and air boats. The report is organized in a question and answer format. The topic of terrain crossing is particularly well covered.

10. Kordenbrock, J. V., and E. Eckoman, "*Summary Report. SKMR-1, Design, Construction and Testing*," Bell Aerospace Co. Rept 2073-928016 (Mar 1966)

The SKMR-1 is approximately 65 feet long by 27 feet wide, with a design weight of 45,000 pounds. The report describes the vehicle and its subsystems through the proposal, development, and testing phases. Noise, vibration, and winterization (not Arctic) are also covered. Operational tests of towing, performance, obstacle clearance, long range mission, etc, are described. A maintenance summary is included which discusses some of the problems and failures encountered.

11. "*Proposal for ACV Amphibious Assault Landing Craft (Bell SK-10)*," Bell Aerospace Co. Rept D7385-953001, (Dec 1969)

The proposal details the overall approach with regard to organization, management, and controls of a two-phase program. Phase one is a study plan concerning preliminary design criteria and craft requirements, configurations, and systems. Also proposed is model testing and value engineering. Phase two is an approach for detail design, manufacturing, and testing. A section is included on the background and experience utilized for the proposal. This proposal includes a material rating table that enables a direct comparison to be made with respect to cost, mechanical properties, manufacturing characteristics, and corrosion resistance.

12. Harting, A., **Selective Bibliography on Air Cushion Vehicles**, National Aerospace Lab, Amsterdam (Netherlands) (Feb 1969)

This bibliography is grouped into 11 sections. Section 1 is general, sections 2 through 10 treat their title subjects exclusively, and section 11 deals with information that may be useful to the ACV worker. Sections 2 through 10 deal with the annular jet, the labyrinth seal, the diffuser, the plenum chamber, air bearing and the levapad, the ram wing, control and navigation, structures and materials, and propulsion, respectively.

13. "*Joint Surface Effect Ship Program-Structural Design Studies for Surface Effect Ships*," Bell Aerospace Co. Final Rept 7363-950001 on Contr MA4687, Phase I, (Dec 1969)

The tasks listed in this report are loads determination, structural material data, cost data, design criteria, procedures, weight factor development, and configuration selection. The gross tonages of the craft considered were 500, 4,000, 7,000, and 10,000. The characteristics desired for a good surface effect ship (SES) structural material are listed and several candidate materials are presented on a rating schedule. For each of the alloys selected a method of fabrication compatible with the material was chosen. The associated material properties and range of commercial sizes available were determined for each material and fabrication concept.

14. "*Joint Surface Effect Ship Program-Structural Design Studies for Surface Effect Ships*," Bell Aerospace Co. Final Summary Rept 7363-950002 on Contr MA4687, Phase II (Dec 1970)

This report includes a coating study with particulars on maintenance areas, environmental effects, protective requirements, and service life. A computer program is developed for determining stresses, weight, and cost when given the material properties, construction and vessel dimensions. Conclusions are drawn which provide a basis and guide for the minimum structural weight design of large surface effect ships. The study results show aluminum and titanium alloys yielding the lowest structural weight fractions. Steel alloys and glass-reinforced plastics showed higher weight fractions. Concerning structural weight, the best design approach studied is a 2000-ton SES fabricated of welded 6Al-2Cb-1Ta-1Mo titanium sheet, rolled, formed extrusions and transverse frames. Total procurement costs point to a 5086 alloy SES as the cheapest with steel and titanium alloys increasingly more expensive. From a cost basis only, the SES should be constructed using the module two fabrication concept of an all-welded structure of formed stringers and sheet with transverse frames. The form and depth of this report is a beneficial aid in the choice of materials and structure.

15. "*Preliminary Design Summary Report*," Bell Aerospace Co. Rept 7385-950007, AALC C150-50, Vol. III, Engineering Report, Section 6, Part 1 (Oct 1970)

This study is mainly a design history of the amphibious assault landing craft and includes numerous illustrations, charts, graphs, and photos with detailed information. For five selected structural configurations and materials there is a manufacturing merit evaluation sheet. There is also a detailed investigation of the welded aluminum 6061 alloy. The design criteria includes the requirements, tactical parameters, and loads assumptions. The technology background and major systems tradeoffs are included with sections on manufacturing evaluation, materials selection, modules and weight summary. Different types of construction are proposed with various hydraulic systems.

16. "*Final Report, Ground Effect Machine Structures Study*," Ryan Aeronautical Co. Rept G-42-62, San Diego, Calif. (Nov 1960)

The vehicle mission is defined for five different craft and size-weight relationships are subsequently developed. The proposed craft are an amphibious assault vehicle, an anti-submarine warfare platform, a cargo lighter, an ocean-going transport, and a reconnaissance car. Aluminum, plywood, and steel structures are considered in the structural design and analysis. The weights for each craft, structural configuration, and material (proposed) is reported.

These craft have gross weights ranging from ½ ton for the reconnaissance car to 3,500 tons for the ocean-going transport. The requirements and characteristics of the largest craft are detailed, including horsepower, aerodynamic drag, engine arrangement, deck area, and floatation area.